Reliability Modeling Development and Its Applications for Ceramic Capacitors with Base-Metal Electrodes (BMEs)

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Acronyms

AEC-Q200	Automotive Electronics Council-Q200 (AEC-Q200)
BME	Base-Metal Electrodes (BMES)
CA	Construction analysis (CA)
CARTS	Capacitor and Resistor Technology Symposium (CARTS)
DPA	Destructive Physical Analysis (DPA)
GSFC	Goddard Space Flight Center (GSFC)
MLCCs	Multi-Layer Ceramic Capacitors (MLCCs)
MTTF	Mean Time to Failure (MTTF)
SCDs	Specification Control Drawings (SCDs)
TTF	Time to Failure (TTF)

Outline

- Summary of NEPP-Funded Deliverables
- Development of a General Reliability Model for BME Capacitors
  - How to build BME capacitors for high-reliability applications
  - How to screen out bad apples
  - How to explain the reliability life difference in commercial automotive-grade BME capacitors
- Summary and Future Work

NEPP-Funded Deliverables for Fiscal Year 2014

- A general reliability model was developed for BME capacitors
- The results were presented at the 2014 International Capacitor and Resistor Technology Symposium (CARTS) and uploaded to the NASA NEPP website
    - D. Liu, "A General Reliability Model for Ni-$BaTiO_3$-Based MLCCs." CARTS Proceedings, Santa Clara, CA pp. 31-47 (2014) (https://nepp.nasa.gov/files/25994/2014-562-Liu-Final-web-CARTS2014-paper-TiO3BME-TN14691.pdf)
    - D. Liu, "Evaluation of Commercial Automotive-Grade BME Capacitors." CARTS Proceedings, Santa Clara, CA pp. 189-203 (2014) (https://nepp.nasa.gov/files/25998/2014-562-Liu-Final-web-CARTS2014-paper-Auto-TN14693.pdf)
- A technical paper won the "Outstanding Paper Award" at CARTS 2014
    - This is the 3rd time in the last four years that this award has been presented to David Liu and his co-author(s)
- A journal paper was accepted for publication in an IEEE Transaction

NEPP-Funded Deliverables for Fiscal Year 2014 (Cont'd)

- Application of NEPP-funded study results to the space/military community's general interest in BME capacitors
  - Continuing participation in the G11 BME Industrial Forum to establish a new MIL performance specification for multilayer ceramic capacitors with thin dielectric layers (to replace the currently used MIL-PRF-123)
  - Selection as one of the seven representatives for a small-scale weekly meeting (NASA GSFC, The Aerospace Corporation, Raytheon, Defense Logistics Agency, AVX, KEMET, Presidio)
- Implementation of a reliability model for NASA documentation for the pre-qualification of BME capacitors
  - Construction analysis (CA) and destructive physical analysis (DPA) requirements in specification control drawings (SCDs) for Virtex-5 at Marshall SFC
  - Pre-qualification requirements in SCD of GSFC S-311-P-838 for BME capacitors with thin dielectrics (*non-NEPP-funded*)
  - A new section in EEE-INST-003 (*non-NEPP-funded*)

Development of a General Reliability Model for BME Capacitors

$$R(t) = R(t=0) \times \{(1-\theta) \times P(t) + (\theta) \times Q(t)\}$$

$$R(t=0) = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$$

Initial reliability

$$P(t) = e^{-\left[\frac{t}{\frac{c}{V_{applied}{}^{n}} \times \left(\frac{d}{\bar{r}}\right)^{n} \cdot e^{\left(\frac{E_{a1}}{kT}\right)}}\right]^{\beta_1}}$$

Reliability for catastrophic failures (modified P-V equation)

$$Q(t) = e^{-\left[\frac{K_0 t}{Ce^{-bE} \cdot e^{\left(\frac{E_k}{kT}\right)}}\right]^{\beta_2}}$$

Reliability for slow degradation (for BME only) (E-model)

Where:

d: dielectric thickness

$\bar{r}$: average grain size

N: number of dielectric layers

α: empirical constant

E: applied electric field

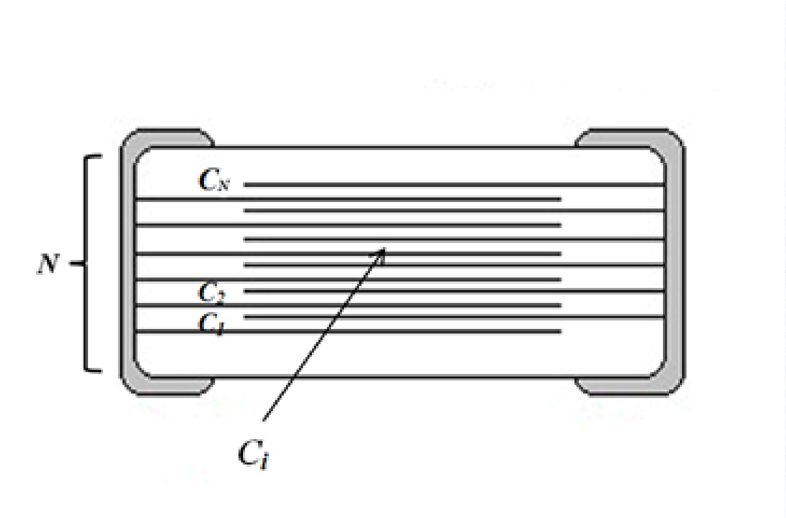
$K_o e^{-\frac{E_k}{kT}}$: degradation rate constant of $V_o^{\cdot\cdot}$

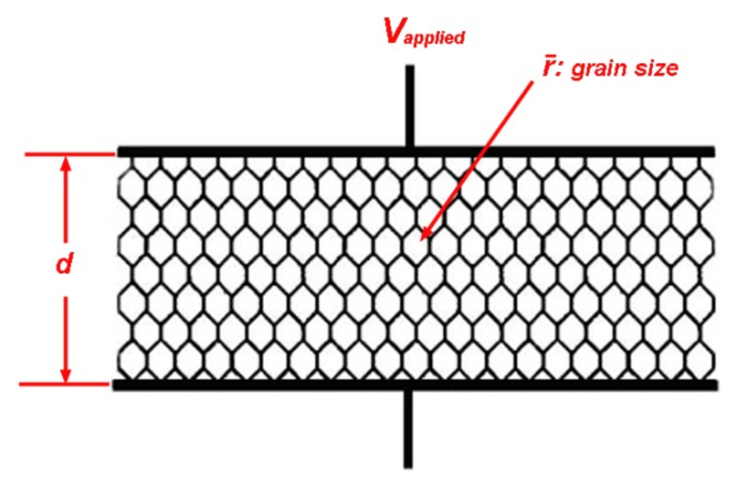
n: power law constant

C, c, and b: constants

θ, β_1, and E_{a1}: percentage, Weibull slope constant, and activation energy for failure mode 1: catastrophic failure

Application Example: Initial Reliability





- When ***t=0***, one has

$$R(t=\mathbf{0}) = \left[\mathbf{1} - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$$

- The initial reliability is only determined by the construction/processing parameters
- Two key parameters for reliability control: average grain size and number of total dielectric layers
- This helps prevent the counterfeiting of commercial BME capacitors for high-reliability applications

Application Example: Initial Reliability (Cont'd)

Life Test Results per MIL-PRF-55681 and -123

					life testing at 2XVr, 125°C	
CAP ID	Grain Size (μm)	Dielectric Thickness(μm)	No. of Dielectric layers N	Calculated R_t	1000 hours	4000 hours
A08X22525	0.305	3.89	211	0.99995	Fail	
B08X33425	0.420	5.80	74	0.99999	Pass	Pass
A08X15425	0.460	9.80	43	1.00000	Pass	Pass
C06X10525	0.440	3.20	150	0.99899	Fail	
A06X10425	0.470	7.89	62	1.00000	Pass	Pass
A12X47425	0.492	10.40	58	1.00000	Pass	Fail
C04X47325	0.386	4.40	60	0.99997	Fail	
B12X47525	0.376	4.34	260	0.99989	Fail	
P08X10425	0.790	20.20	23	1.00000	Pass	Pass
B06X10516	0.273	2.29	179	0.99948	Fail	
A08X47416	0.319	3.75	208	0.99992	Fail	
B12X68416	0.375	6.21	64	1.00000	Pass	Pass
C08X22516	0.224	3.81	212	0.99999	Pass	Fail
B08X22516	0.340	3.23	230	0.99969	Fail	
B08X56416	0.373	4.21	80	0.99996	Pass	
C08X47516	0.230	2.49	260	0.99984	Pass	Fail
B12X10516	0.475	7.82	99	1.00000	Pass	Pass
B04X10416	0.342	3.05	67	0.99987	Fail	
B12X10606	0.365	3.11	348	0.99908	Fail	
B04X10406	0.323	2.50	70	0.99967	Fail	
B08X22506	0.419	3.42	230	0.99922	Fail	
A08X10406	0.490	12.50	34	1.00000	Pass	Pass
B06X22406	0.373	4.01	67	0.99996	Pass	Fail
P06X10405	0.770	12.60	24	1.00000	Pass	Pass

$$R(t=0) = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} = 1.00000$$

- Some commercial BMEs passed the life test. Life testing of another 8 groups of BME capacitors is still in progress!
- All automotive-grade BME MLCCs meet this requirement
- The formula described can be used as a simple rule of thumb when designing BME MLCCs for high-reliability applications
- This also indicates that high-reliability MLCCs must be built for this purpose; one cannot improve capacitor reliability by "up-screening"

Selection Criterion and Number of Zeros

$$\boldsymbol{R(t=0)=\left[1-\left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}=1.00000}$$

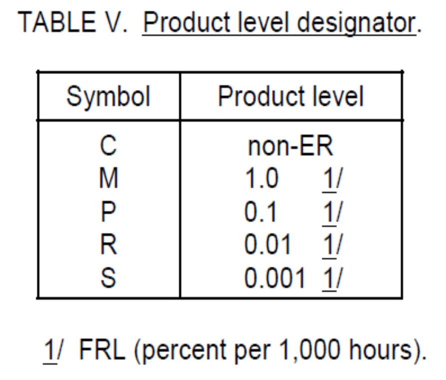


TABLE V. Product level designator.

Symbol	Product level
C	non-ER
M	1.0 1/
P	0.1 1/
R	0.01 1/
S	0.001 1/

1/ FRL (percent per 1,000 hours).

MIL-PRF-55681, paragraph, 1.2.1.7

→

BX life to failure rate:

M: B1% life
P: B0.1% life
R: B0.01% life
S: B0.001% life

BX life to Reliability:

M: B1% life $= \eta'\{-ln[R(x_1\%)]\}^{1/\beta}$ **where $R(x_1\%)$ =0.99**
P: B0.1% life $= \eta'\{-ln[R(x_2\%)]\}^{1/\beta}$ **where $R(x_2\%)$ =0.999**
R: B0.01% life $= \eta'\{-ln[R(x_3\%)]\}^{1/\beta}$ **where $R(x_3\%)$ =0.9999**
S: B0.001% life $= \eta'\{-ln[R(x_4\%)]\}^{1/\beta}$ **where $R(x_4\%)$ =0.99999**

The number of zeros represents the failure rate level!

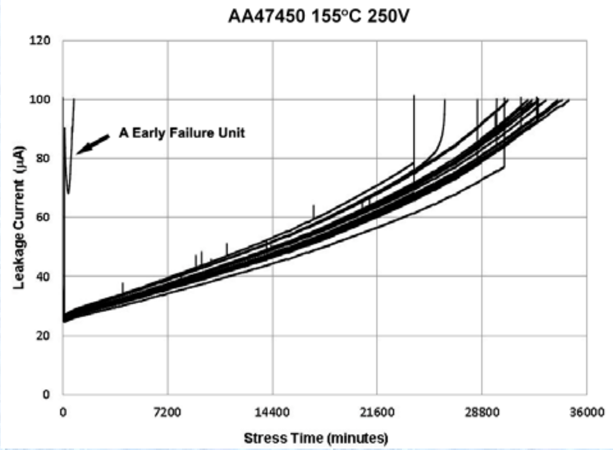
- BME capacitors that meet this requirement may not all pass the reliability life testing per MIL-PRF-55681 or MIL-PRF-123
- BME capacitors that did not meet this requirement would have a high chance of failure during life testing!
- An empirical criterion of construction analysis can be used to reject a BME capacitor for high-reliability use prior to tedious life testing

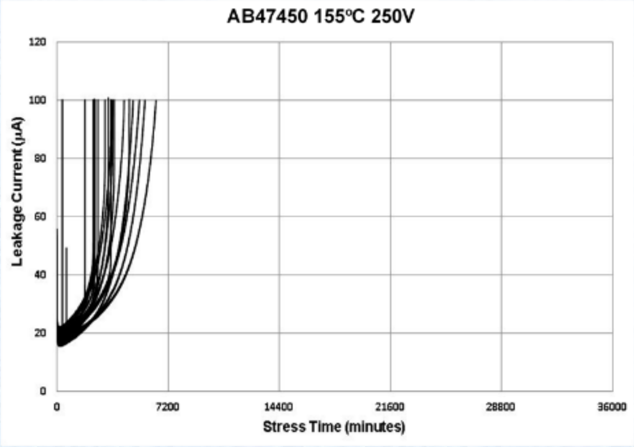
Reliability Life in Automotive-Grade BME Capacitors

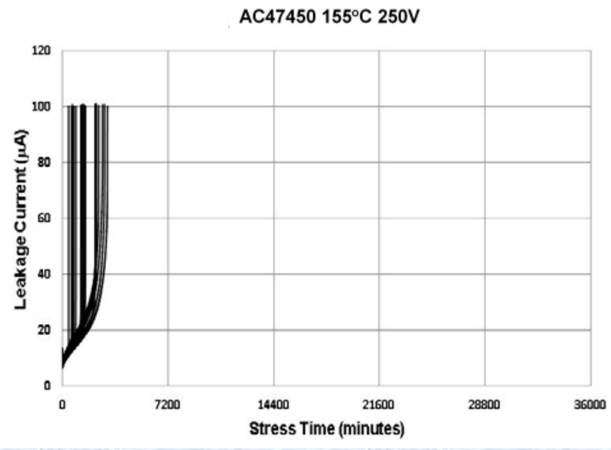
Part ID	Stress Level	E (kV/mm)	Volts/Grain
AA47450 0.47μF, 50V, 0805 Manufacturer A 98 layers BaTiO$_3$ thickness = 6.39 μm Ave. grain size = 0.38 μm	250V, 175C	39.1236	14.75
	225V, 165C	35.2113	13.27
	250V, 165C	39.1236	14.75
	250V, 155C	39.1236	14.75
	315V, 155C	49.2958	18.59
AB47450 0.47μF, 50V, 0805 Manufacturer B 100 layers BaTiO$_3$ thickness = 5.80 μm Ave. grain size = 0.33 μm	250V, 175C	43.0886	14.13
	225V, 165C	38.7797	12.72
	250V, 165C	43.0886	14.13
	250V, 155C	43.0886	14.13
	315V, 155C	54.2916	17.81
AC47450 0.47μF, 50V, 0805 Manufacturer C 103 layers BaTiO$_3$ thickness = 8.10 μm Ave. grain size = 0.40 μm	250V, 175C	30.8642	12.45
	225V, 165C	27.7778	11.20
	250V, 165C	30.8642	12.45
	250V, 155C	30.8642	12.45
	315V, 155C	38.8889	15.68

- BME MLCCs made with the same chip size, capacitance, and rated voltage, and that are qualified to the same reliability level (AEC-Q200), were processed for construction analysis to reveal the number of dielectric layers, average grain size, and dielectric thickness
- These BME capacitors were then degraded at similar levels of external stresses as characterized by electric field (kV/mm) and volts/grain

MTTF and Leakage Current of BME MLCCs


AA47450 155°C 250V


AB47450 155°C 250V


AC47450 155°C 250V

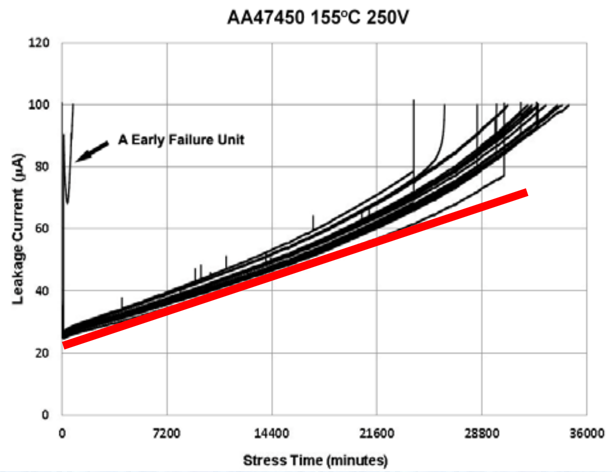
Mean Time to Failure (MTTF in Minutes) of BME Capacitors

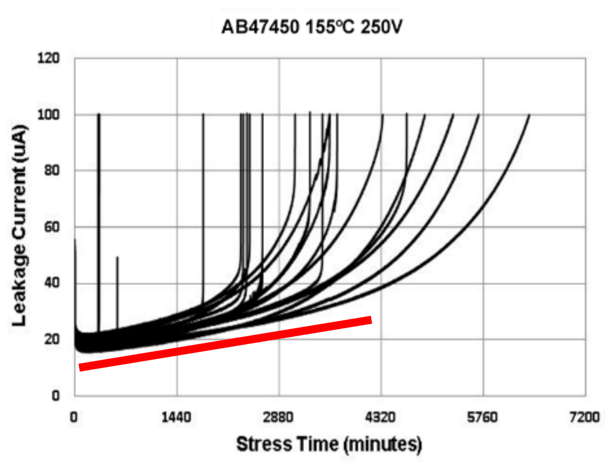
Test Conditions	AA47450	AB47450	AC47450
250V, 175C	1447	450	319
300V, 165C	2506	479	298
250V, 165C	8208	1140	626
225V, 165C	16396	2066	1046
250V, 155C	32760	3659	1679

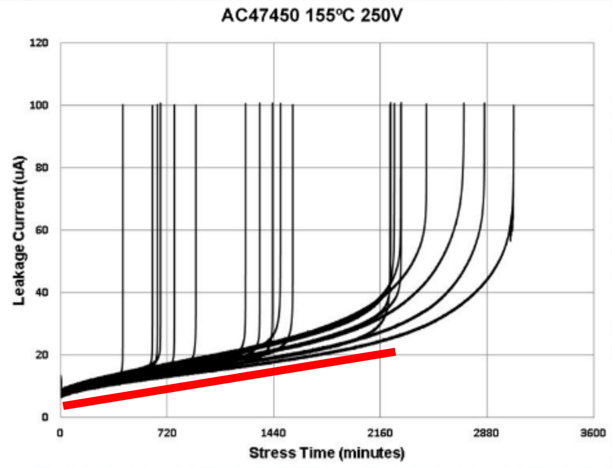
- Both time to failure (TTF) and leakage current of each capacitor device were recorded
- Reliability life, as characterized by MTTF, was more than one magnitude in difference among the three capacitor lots
- The leakage current patterns also reveal very different characteristics

$$\boxed{MTTF = \eta\Gamma(1+\beta^{-1})}$$

Leakage Current vs. Stress Time Characteristics

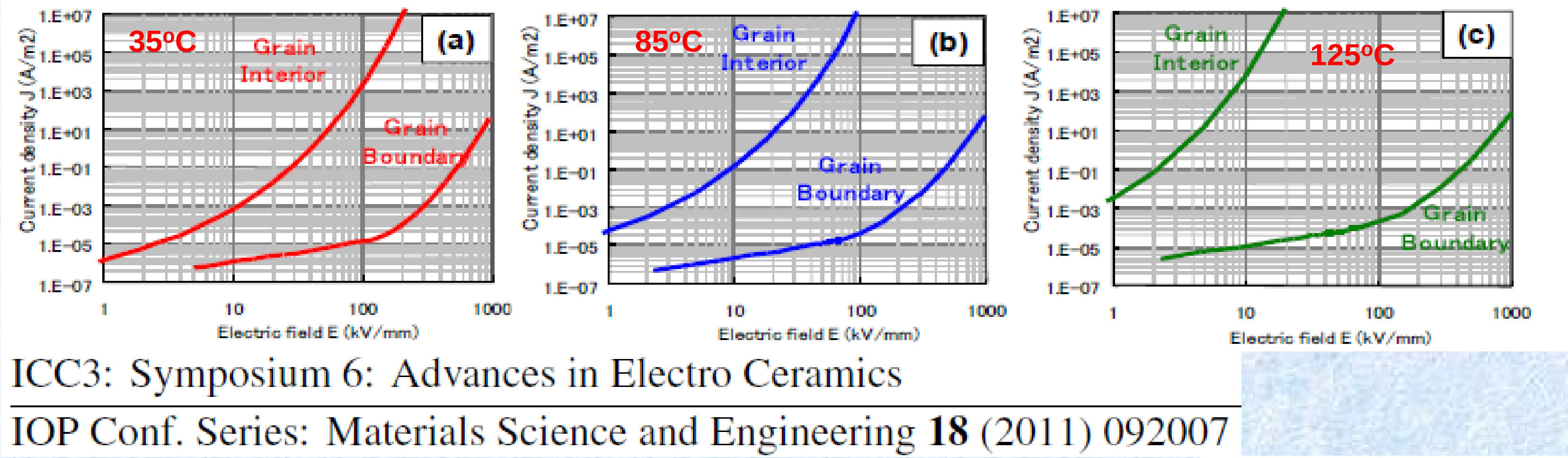






- MTTF is highly dependent on failure mode. Two failure modes have been identified:
  - <u>Catastrophic</u>: a time-accelerating increase in leakage current that is mainly due to existing processing defects or to extrinsic defects
  - <u>Slow degradation</u>: a near-linear increase in leakage current against stress time; this is caused by the electromigration of oxygen vacancies (intrinsic defects)
- All AC47450 units failed at very low leakage current levels, and all failed with a catastrophic failure mode
- Most of the AA47450 units failed with slow degradation
- AB47450 units revealed a mixed failure mode between those of AC47450 and AA47450
- For a certain period of time, leakage current vs. stress time showed an exponential characteristic

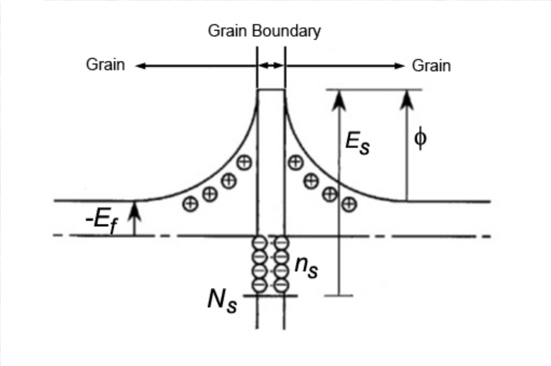
Assumption I: Existence of Depletion Layers in BME MLCCs



ICC3: Symposium 6: Advances in Electro Ceramics

IOP Conf. Series: Materials Science and Engineering **18** (2011) 092007

- The microstructure of each ceramic grain is inhomogeneous. Significant resistivity differences often have been reported due to the inhomogeneity between a grain boundary and the interior of a grain.



- The existence of double Schottky barrier layers has been proposed to describe this inhomogeneity.

Barrier height: $\phi = \dfrac{e^2 N_d d^2}{2\varepsilon_0 \varepsilon_r}$

The resistivity of BME MLCCs: $$\boldsymbol{\rho = \rho_0 e^{\left(\frac{\phi}{kT}\right)}}$$

Depletion layer: $d = \dfrac{n_s}{2N_d}$

Assumption II: Oxygen Vacancy Entrapment

- When a migrating oxygen vacancy is approaching a grain boundary, it has two options: cross over it, or be trapped/localized
- Computational analysis shows that trapping of oxygen vacancies at grain boundaries is *energetically* favorable (Oyama, et al., 2010)
- When it is trapped, two electrons must be captured to meet the electrical neutrality condition:

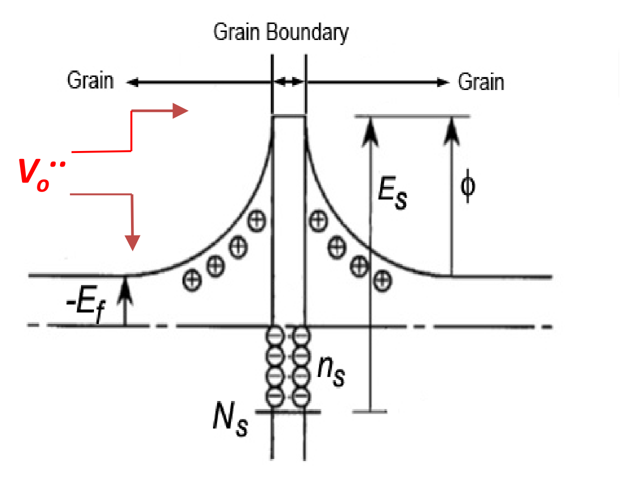
$$V_O^{\bullet\bullet} + 2e' = V_O$$

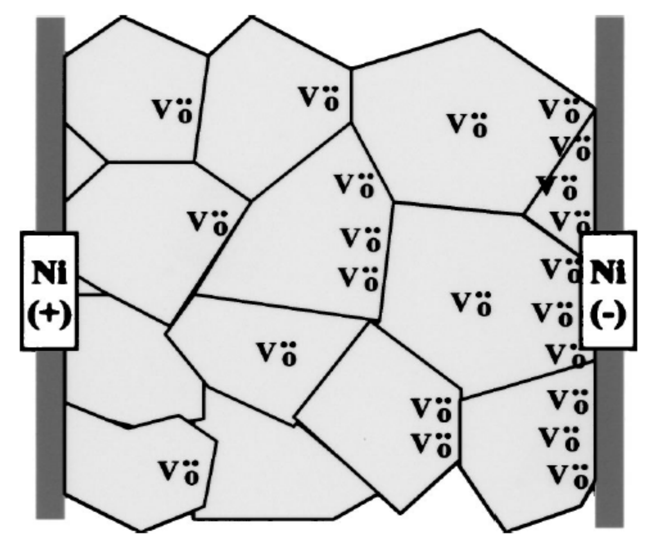
- Two electrons will be compensated by the space charges:

$$Ti^{4+} + e' \rightarrow Ti^{3+}$$

and/or $$Ti^{3+} + e' \rightarrow Ti^{2+}$$

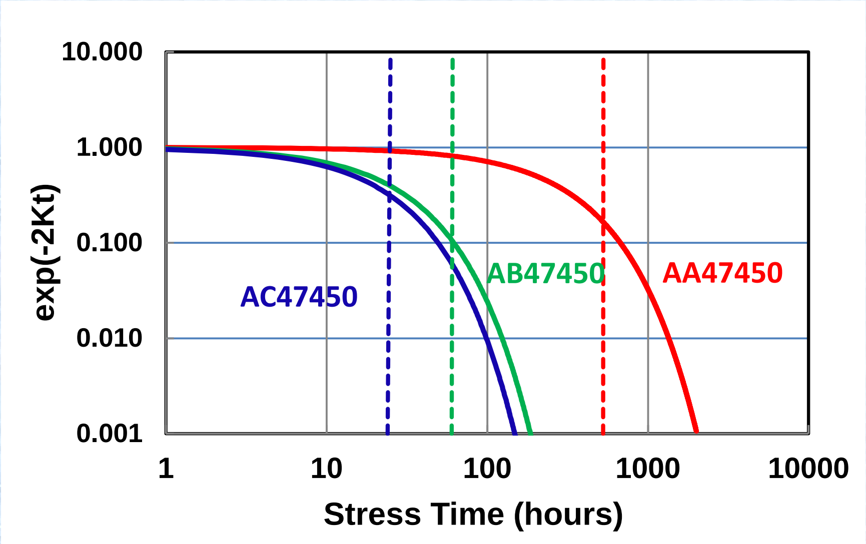
- This will reduce the barrier height and lower the Fermi level as well as $n_s(t)$
- This presentation only discusses entrapment at grain boundaries

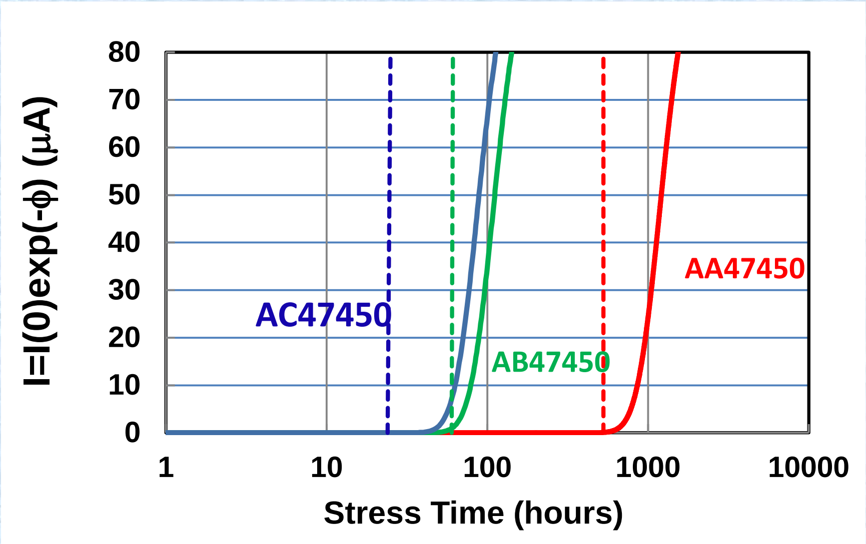




G.Y. Yang, E.C. Dickey, C.A. Randall, (2004)

Calculated IR Degradation in BME MLCCs





- The calculated IR degradation based on the entrapment of oxygen vacancies at depletion layers at grain boundaries matches well with the measured leakage current time dependence
- The activation energy and reaction constants from the model reveal meaningful results

	$K_0 e^{\frac{-E_k}{kT}} (hour^{-1})$		
Capacitor ID	E_k (eV)	K_0 at 398K (125°C)	K_0 at 428K (155°C)
AA47450	1.65	7.38×10^{-5}	2.10×10^{-3}
AB47450	1.63	6.76×10^{-4}	1.86×10^{-2}
AC47450	1.11	4.94×10^{-3}	4.73×10^{-2}

$$\boldsymbol{\phi(t) = \phi(0) \cdot e^{-2Kt} = \phi(0) \cdot e^{-\frac{2t}{MTTF}}}$$

$$\boldsymbol{I(t) = I_0 exp\left(-\frac{\phi(t)}{kT}\right)}$$

Summary and Future Work

- A general reliability model for BME capacitors was developed
- The model can be used as a guideline for designing BME MLCCs for high-reliability applications
- The model can also be used as a screening criterion to reject BME capacitors
- The results of this NEPP-funded study have been implemented in a number of NASA documents
- The effort has also been extended to the G11 BME Industrial Forum to establish a new MIL performance specification for multilayer ceramic capacitors
- The model has been used to explain the reliability life difference in automotive-grade BME capacitors
- The model needs to be extended for hazard rate evaluation
- Continuous life testing of BME capacitors is needed to validate the proposed model